

Hydrological change at Lake Clifton, Western Australia – Evidence from hydrographic time series and isotopic data

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ABSTRACT

The existence of the unique thrombolite reef at Lake Clifton, Western Australia, relies on a delicate hydrological balance between freshwater input and evaporation driven salinity. Time series hydrographic, in conjunction with hydro-geochemical and stable isotope data, are applied to understand the lake's hydrological regime for the time period 2008–2010. Comparisons with previous multi-decadal hydrologic data are also made to identify longer-term system changes. Water level and salinity data indicate ongoing rainfall and groundwater inputs to Lake Clifton's water balance, however, decreasing rainfall and increasing salinity are threatening the current hydrological balance of the lake and thus potentially its conservation values. Stable isotope data ($\delta^{18}\text{O}$ and $\delta^2\text{H}$) indicate a well-mixed lake water body dominated by evaporative processes, and a possible change in lake hydrology in recent decades. Aqueous elemental data support this, suggesting a possible alteration in the lake's hydrological balance resulting in an increase of the total dissolved solids from groundwater inflows from the eastern side of the lake. Rising temperatures, reduced rainfall and greater evaporation rates combined with reduced fresh groundwater input are resulting in likely groundwater migration of saline groundwater from the Hayward chain of hypersaline lakes and thus in a redistribution of the greater lakes system salt balance towards Lake Clifton, altering the lakes ecosystem.

KEYWORDS: Stable water isotopes, Altered hydrology, RAMSAR, Thrombolites

INTRODUCTION

Increasing salinity, declining water levels, decreasing rainfall, increasing urban encroachment and greater nutrient inputs are key pressures on the current hydrological and ecological balance of the RAMSAR listed Lake Clifton, southwest Western Australia. These threats to conservation values have been highlighted in numerous studies, which have characterized the environmental dynamics of Lake Clifton, including hydrogeological (e.g. Moore, 1987, Commander, 1988, Deeney, 1989, Barr, 2003, Smith *et al* 2010), geochemical (e.g. Moore and Turner, 1988, Davies and Lane, 1996, Rosen *et al* 1996, Knott *et al* 2003, Luu *et al* 2004, Lane *et al* 2013, Smith *et al* 2010) and biological (e.g. Moore *et al* 1984, Burne and Moore 1987, Moore and Burne 1994, John *et al* 2009) investigations. In the northeast corner of the lake an extensive (6 km²) thrombolite reef occurs, the largest in the southern hemisphere (Moore *et al* 1987, Luu *et al* 2004). Restricted to sub-tidal, sub-littoral and supra-littoral environments of water bodies (Neil, 1984) thrombolites are defined as discrete organo-sedimentary structures, produced by some combination of sediment trapping, binding and precipitation as a result of metabolic activity of micro-organisms (Moore and Burne, 1994). At Lake Clifton, the development and continued persistence of thrombolites has been attributed to continuous inputs of groundwater from the eastern

boundary of the lake, providing suitable habitat for microbial mats to form calcified microbialite structures (e.g. Moore *et al* 1984, Burne and Moore, 1987, Moore, 1987). Alterations to this sensitive ecohydrological system are thought to present an increasing threat to the existence of microbial mats responsible for the thrombolite reef (e.g. Moore, 1991, Knott *et al* 2003, Smith *et al* 2010). However, one of the limitations of many previous hydro-geochemical studies has been the sporadic nature of datasets, effectively only providing snapshots of lake system dynamics through time. As a result, knowledge gaps continue to exist, in particular intra-seasonal hydrological data. In this study, we present time series hydrological and hydro-geochemical data for surface, sub-surface, ground and rainwaters spanning a two-year period (2008–2010). We assess the seasonal hydrological functioning of Lake Clifton and importantly combine our new data with historic geochemical and isotopic data to gain a more recent perspective of hydrology and hydrochemical change to the system in recent decades. Importantly this greater appreciation of hydrological change at Lake Clifton can provide insights into how such systems are being modified as a result of climate change alterations to hydrological systems, and the need for higher resolution monitoring programs to identify these rapid changes.

Study Site

Lake Clifton is located in the southern section of the narrow Swan Coastal Plain, southwestern Western

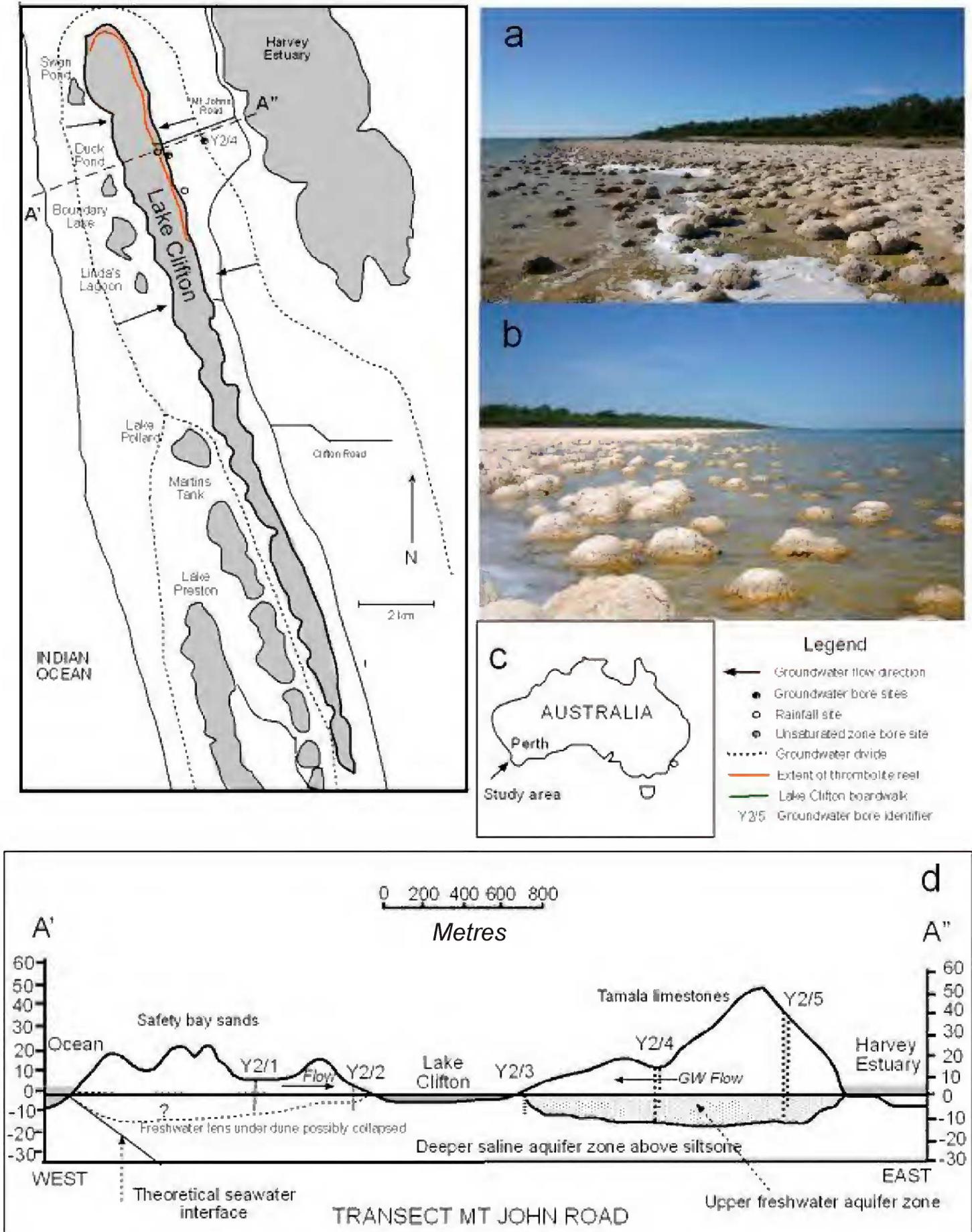


Figure 1. Location map for Lake Clifton within the Yalgorup Lakes System in relation to Perth and greater Western Australia region. Inset a. Thrombolites during summer low water level looking north from Boardwalk. Inset b. Thrombolites during winter high water level looking south from Boardwalk. Inset c. Location of Lake Clifton in southwest Western Australia. Inset d. Hydrogeological cross section of Lake Clifton along Mt Johns Road, including location of Bore network (Modified from Commander 1988). The aquifer system presented in the cross section consists of an upper fresh water lens (referred to in this study as the upper freshwater aquifer) overlying the greater highly saline body.

Australia. It is part of the Yalgorup Lakes system and is bounded by the Precambrian Yilgarn Craton to its east and the Indian Ocean to the west (Figure 1); (Playford *et al* 1976, Commander, 1988, Coshell and Rosen, 1994). The Yalgorup lakes are located in elongated depressions parallel to the coastline, separated by a series of stabilized Pleistocene dune ridges and Holocene dunes. The Pleistocene dune ridges formed between 30 ka to 40 ka BP and Holocene dunes formed during a period of coastal progradation following sea-level changes at 3 to 6 ka BP (Thom and Chappell, 1975, Commander, 1988, Semenuik, 1995). Near surface geology (Figure 1; Inset A), consists predominantly of Quaternary age sands (including calcarenites and minor limestone), underlain by Tamala limestone (Pleistocene), of variable thickness (10 to 100 m) overlying Cretaceous shale and siltstones of the Leederville Formation (Playford, 1971, Commander, 1988, Semenuik, 1995). Sands dominate to the west, while the marine and estuarine fossil containing Tamala Limestone is more prevalent in the central and eastern parts, commonly outcropping near the eastern shoreline of Lake Clifton with the Spearwood Dune System further to the east (McArthur and Bartle, 1980).

The lake is deepest (3 m) in the northern section, and is permanently inundated, whilst the southern third of the lake is ephemeral, drying out over summer (December to February) (Moore *et al* 1987). The thrombolite reef is located on the eastern shoreline in the north of the lake, and is submerged during the winter and spring seasons following increased rainfall (Moore *et al* 1987, Luu *et al* 2004, John *et al* 2009, Smith *et al* 2010). The lake does not experience surface outflows and is thought to receive only occasional minor surface water inputs (Commander, 1988, Davies & Lane, 1996). Hence, Lake Clifton is a groundwater discharge and groundwater through-flow lake that reflects the balance between evaporation, rainfall and groundwater inflow (Moore, 1987, Commander, 1988, Moore, 1993). Previous Total Dissolved Solids (TDS) data indicated that Lake Clifton is predominantly hypersaline, punctuated only by a period of hyposaline conditions in late winter, when rainfall exceeds evaporation (Moore *et al* 1984). Lake TDS has been rising over recent decades (Lane *et al* 2013) with TDS as high as 90 g/L⁻¹ recorded in May 2010 (Noble, 2010).

In the Yalgorup lakes system groundwater flow is typically away from the elevated dune ridge areas towards local drainage features such as the coastal lakes and wetlands (e.g. Deeney, 1989). This is apparent for Lake Clifton with groundwater flow from ridges to both the east and west of the lake (Figure 1). A local unconfined groundwater system interacts with the lake (Moore, 1987, Deeney, 1989, Commander, 1988), and is comprised of an upper fresh (2 g.L⁻¹) thin (20 m) zone, overlying a lower dense hypersaline aquifer (>30 g.L⁻¹) to the east. The upper fresh aquifer is directly recharged by rainfall and inflow from the east, while the seawater wedge and downward leakage from saline lakes in the Yalgorup system are the likely origins of the high TDS in the lower aquifer (Moore, 1987, Commander, 1988). The surface water level of Lake Clifton is typically close to or just below sea level. Hydrological boundaries (Figure 1) of Lake Clifton's catchment are the Lake Preston flow system to the south and Martins Tank and

Harvey Estuary groundwater divides to the west and east respectively (Commander, 1988).

METHODS

Monitoring Sites

Four sites each representing key components of Lake Clifton's water balance were chosen for high resolution monitoring from 2008 to 2010. The surface water site is located at the northern end of the Lake Clifton boardwalk, where annual water level and salinity monitoring has been ongoing for several decades (Lane *et al* 2013). The upper fresh aquifer was represented by a 15 m deep bore (Department of Water – Bore# Y24A) located approximately 1 km east of the boardwalk. All water levels measured as metres above local datum (deepest point of lake), were then adjusted to Australian Height Datum (AHD) which requires a +4.035 m addition. A further hand augured bore a shallow (1.5 m below ground level) located on the lake's eastern edge approximately 10 m south of the boardwalk was also monitored. The depth of this bore is located in the unsaturated zone, well above the aquifer and fills with sub-surface inflow during the winter and spring seasons. The top of the casing is sufficiently high (1 m) not to be inundated during seasonal peaks in lake water level.

Temperature, pH, Salinity/Electrical Conductivity (EC), and water level data for Lake Clifton surface water were measured at four hour intervals using a multi-sonde logger (HYDROLAB #MS5). Levels were measured as a pressure reading by the multi-sonde, which was converted to a level of water, including a correction for lake TDS. Depth of water at the boardwalk was then converted to total lake depth by inference of difference between lake level at boardwalk and that at the deepest part of the lake (e.g. Lane *et al* 2013). Temperature, pH, and TDS/EC measurements were compared to periodic manual measurements performed with a multi-parameter probe (OTT QUANTA-G). Three point (pH) and two point (EC) calibration of the multi-sonde logger and multi-parameter probe were undertaken using 4,7,10 pH buffers and 1000 and 10000 mS/cm calibration standards respectively. For the sub-surface waters and Surficial Aquifer bores, water level, Salinity/EC and temperature were recorded using CTD-DIVER automated data-loggers (SCHLUMBERGER #DI272), with salinity/EC calibrated using the same two point EC calibration standards. Water pressure heads (HPa) measured by the CTD-DIVERS were corrected for daily fluctuations in atmospheric barometric pressure measured in bores using a third independent CTD logger placed at the Lake Clifton boardwalk. Periodic manual measurements of bore levels were then applied to correct data to water level in metres above lake floor, and subsequently to Australian Height Datum (AHD). EC measurements have been converted to TDS using the relationships presented in Lane *et al* (2013). Monthly averages and standard deviations of all parameters were derived from approximately individual 180 measurements (six daily). Independent bi-annual manual measurements at Lake Clifton undertaken by Department of Parks and Wildlife, Busselton, Western Australia (Lane *et al* 2013) were used as comparisons to our monthly averages. Local rainfall was measured

Table 1. Average monthly water level, salinity, pH and temperature measurements for Lake Clifton. Period November 2008 to November 2010. Data for months August 2010 onwards are manual readings

	Rainfall mm	Water Level m AHD	Stdev	Salinity ppt	Stdev	pH	Stdev	Temp Celcius	Stdev
Nov-2008	47.2	8.19	0.1	44.4	0.8	8.5	0.1	20.6	2.2
Dec-2008	5.4	8.11	0.0	47.1	0.7	8.5	0.0	22.0	1.0
Jan-2009	2.8	7.94		64.5		8.4		21.5	
Feb-2009	12.4	7.75	0.0	70.7	0.0	8.3	0.1	21.2	1.1
Mar-2009	5.0	7.57	0.1	70.7	0.0	8.1	0.1	22.2	1.6
Apr-2009	3.4	7.53	0.1	70.7	0.0	8.1	0.0	20.0	1.4
May-2009	54.8	7.54		70.7	0.0	8.2		16.0	
Jun-2009	184.2	7.78	0.1	67.5	1.7	8.4	0.1	13.6	0.8
Jul-2009	129.2	8.09	0.1	60.5	3.2	8.1	0.2	13.7	0.8
Aug-2009	90.6	8.15	0.1	53.9	1.1	7.8	0.0	15.6	1.2
Sep-2009	107.4	8.21	0.1	49.4	0.6	8.6	0.1	16.1	1.0
Oct-2009	12.2	8.21	0.1	50.2	0.9	8.7	0.1	19.1	1.6
Nov-2009	39.4	8.10	0.1	53.8	1.0	8.7	0.1	21.4	2.1
Dec-2009	0	8.02	0.1	59.5	2.9	8.6	0.1	22.9	1.7
Jan-2010	0.2	7.72	0.1	70.1	1.1	8.3	0.1	24.7	1.8
Feb-2010	2.8	7.52	0.0	70.7	0.0	8.1	0.1	24.6	2.1
Mar-2010	68.2	7.48	0.0	70.7	0.0	7.9	0.2	23.5	2.1
Apr-2010	26.4	7.49	0.1	70.7	0.0	7.9	0.1	20.4	1.5
May-2010	75.4	7.58	0.1	74.2*		7.7	0.2	16.9	1.4
Jun-2010	132.8	7.79	0.1	70.7	0.0	7.4	0.0	14.8	1.3
Jul-2010	131	7.85	0.1	67.1	0.3	7.4	0.0	12.9	0.6
Aug-2010	88.8	7.99		59.2		7.8		14.3	
Sep-2010	18.6	7.95		51.8		7.5		15.9	
Oct-2010	15.4	4.04							
Nov-2010	9.2	7.93		62.0		8.1		21.3*	

Salinity measurement for May 2010 was a manual reading of 74.2 ppt. Monthly average of logger data was 70.7 with stdev of 0.0.

Table 2. $\delta^{18}\text{O}$ and $\delta^2\text{H}$ isotope data (per mille) for Lake Clifton 2010.

Sample ID	Type ^c	Location	Date	$\delta^2\text{H}$	$\delta^{18}\text{O}$
YG23	LW	1km south of boardwalk 1m depth	13/05/2010	11.2	1.47
YG21	LW	At Boardwalk depth gauge 1m depth	13/05/2010	16.7	2.89
YG7	LW	1km south of boardwalk 1m depth	10/09/2010	5.4	0.41
YG15	LW	At Boardwalk depth gauge 1m depth	10/09/2010	6.6	0.84
YG30	LW	At boardwalk depth gauge 1m depth	18/11/2010	19.4	3.25
YG33	LW	At boardwalk depth gauge 1m depth	23/11/2010	19.9	3.51
YG31	LW	10m west from Boardwalk logger 1m depth	18/11/2010	19.3	3.40
YG32	LW	15m west from Boardwalk logger 1m depth	18/11/2010	18.1	3.43
YG34	LW	20m west from Boardwalk logger 1m depth	18/11/2010	20.4	3.45
YG35	LW	30m west from Boardwalk logger 1m depth	18/11/2010	18.2	3.27
YG36	LW	40m west from Boardwalk logger 1m depth	18/11/2010	19.1	3.12
YG39	LW	Lake Clifton north west corner 1m depth	23/11/2010	24.0	4.38
YG40	LW	Lake Clifton north east corner 1m depth	23/11/2010	22.0	3.75
YG37	SW	Shoreline 20m north of Boardwalk	23/11/2010	10.5	1.91
YG38	SW	Shoreline 40m south of Boardwalk	23/11/2010	8.9	2.08
YG14 A	SSW ^A	Bore 10m south of Boardwalk	13/05/2010	-6.0	-1.50
YG14 B	SSW ^A	Bore 10m south of Boardwalk	10/09/2010	-5.3	-0.91
YG12	GW	B4 Clifton East	10/09/2010	-19.6	-4.38
YG16	GW	DoW Bore Y24A 1KM East 11m depth	10/09/2010	-15.6	-2.50
YG1	GW	DoW Bore Y32A 1KM East 11m depth	10/09/2010	-17.0	-3.84
YG11	GW	B2 Martins Tank	10/09/2010	-20.8	-4.54
YG28	P	Yalgorup Rainfall	10/06/2010	-13.2	-4.27
	P	Perth Rainfall ^B		-17.4	-3.85

^A Lake Clifton seep waters are sub-surface waters expressed at surface on lake eastern edge

^B Perth Rainfall Average isotope values from Turner and Townley 2006

^C LW- Lake water, SW-surface water, P-Precipitation, GW-Groundwater, SSW-sub-surface water

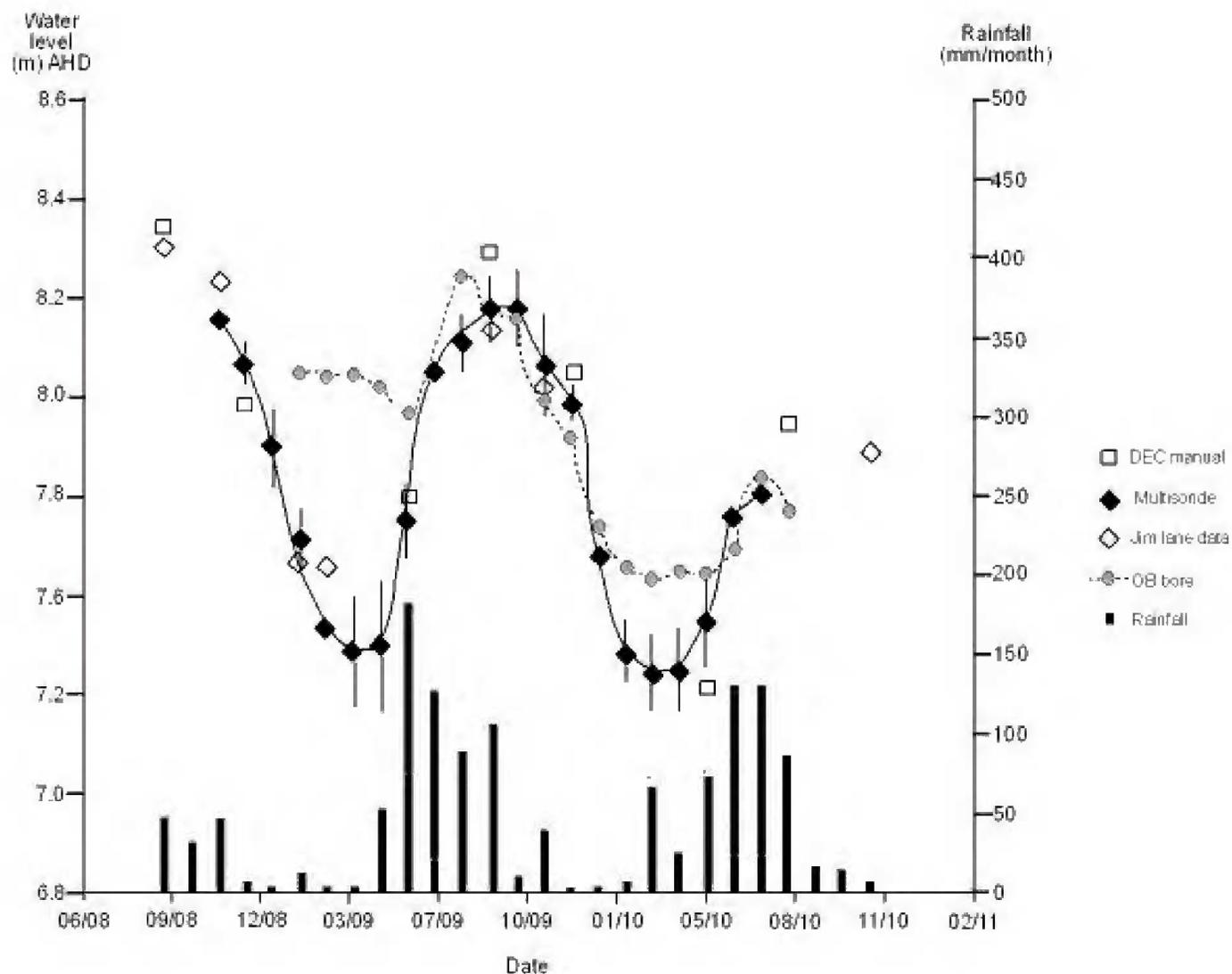


Figure 2. Manual and automated logger measured water levels (metres of depth gauge local datum; +4.035m AHD) for Lake Clifton and the observation bore (1 m BGL), representing unsaturated zone adjacent to the boardwalk for the period November 2008 to November 2010. Also presented are manual lake level measurements (metres) taken for the same period by Lane *et al* 2013. Monthly Rainfall totals representing a composite of measured local rainfall gauge and Mandurah Bureau of Meteorology Station #9977 are also presented.

using a HOBO tipping bucket rain gauge (*ONSET #RG3*) located in an open field on the lakes eastern edge one km south of the boardwalk. Rainfall volumes were logged as 9 am daily totals (24 hr) and validated against data collected at the Bureau of Meteorology Mandurah station (BoM # 9977).

Sample collection

Surface waters were collected manually from specific locations by wading out with bottle or using long pole sampler. Bores were purged (3x volume) and sampled. A single rainfall sample was collected the morning after a 60 mm+ rainfall event on 22nd May 2010 from rain gauge. Water samples for major ion analysis were filtered to <0.45 μm , filed in HDPE bottles to overflowing and stored at <4 °C until analysis. Separate 50 ml samples were also collected sealed in small brown glass bottles and stored in darkness at <4 °C for $\delta^{18}\text{O}$ and $\delta^2\text{H}$ analysis.

Stable Isotope Analysis

Stable water isotopes $\delta^{18}\text{O}$ and $\delta^2\text{H}$ were analysed at the Natural Isotopes Laboratory (Perth, Western Australia)

with a DLT-100 Liquid-Water Isotope Analyser (Los Gatos Research Inc., Mountain View, CA, USA). Each sample was analysed six times, with the first two being discarded and the last four averaged. Working standard waters, calibrated against IAEA reference waters Vienna Standard Mean Ocean Water-2 (VSMOW), Greenland Ice Sheet Precipitation (GISP) and Standard Light Antarctic Precipitation-2 (SLAP2), were interspaced with the samples for calibration. Data were normalised following Coplen (1988) and expressed as $\delta^{18}\text{O}$ and $\delta^2\text{H}$ per mille (‰) relative to VSMOW. Analytical precision is 0.04 ‰ for $\delta^{18}\text{O}$ and 0.3 ‰ for $\delta^2\text{H}$ (Table 2).

Anions and Cations Analysis

Major Ion analysis (Mg, Ca, Na, K, Cl, Br, F, SO_4^{2-}) of water samples was undertaken at the Perth Water Chemistry Centre, East Perth. Analytical accuracy was checked with an electrical balance to identify the electrical neutrality, with a <5 % deviation between anions and cations considered to be acceptable (Appelo and Postma, 1993).

RESULTS

Lake Clifton Surface Water

Seasonal water level fluctuations of approximately 1 m were observed in Lake Clifton between November 2008 and November 2010 (Figure 2). Minimum lake levels (7.2 m AHD) are observed between May and June, while the highest are in September–November (8.2 m AHD). Measured levels of TDS are significantly greater than seawater (35 g.L⁻¹) for the entire monitoring period and fluctuate between 40 and 70 g.L⁻¹ seasonally, in an inverse fashion to water level (i.e. TDS lowest in September–November). However, for several months each summer during the observation period salinity reaches the maximum threshold of detection (70 g.L⁻¹) for the Hydrolab multi-sonde. The highest manual TDS measurement, (74 g.L⁻¹) was recorded in May 2010, using the Quanta-G multi-probe. Furthermore, TDS appears to stay above the 70 g.L⁻¹ maximum measurement for the Hydrolab for more months in 2010 than it does in 2009. Lake water temperature varies between 10 °C and 30 °C seasonally with the highest evident in late summer (February–March) and the lowest during the late winter (August–September). Slightly alkaline (8.5) to neutral (7) pHs are observed for the lake water, with most basic (8.5 – 9) values observed in November coinciding with the periods of highest water level. Conversely a more neutral pH (7 – 7.5) is observed during the start of winter when lake levels are at their lowest.

Groundwater

Significant differences in the unsaturated zone waters and upper fresh aquifer were observed between November 2008 and August 2010. The upper fresh aquifer exhibits relatively consistent levels (11.4 to 11.6 m below AHD) is fresh (1 to 2 g.L⁻¹) and mildly alkaline pH (8 to 8.5). In comparison the unsaturated zone water levels and salinity are much more variable. Water levels between 7.7 and 8.3 m AHD (highest in the late winter 2009) and remain at or slightly above the base of the lake. Seasonal change for 2010 and 2009 is of a similar magnitude, although lower levels were observed in 2010 (7.7 to 7.9 m AHD) compared to 2009 (8.1 to 8.3m AHD). The TDS of the unsaturated zone waters ranged between 12 to 26 g.L⁻¹ (greatest in the summer months of 2010), significantly higher than upper fresh aquifer, yet much lower than the lake water. The unsaturated zone waters are likely representative of rainfall runoff infiltrating into the lake.

Rainfall

Rainfall totals derived from our data and correlated with the Bureau of Meteorology Mandurah station (BoM # 9977) indicate that in 2010 Lake Clifton experienced less precipitation (530 mm) than in 2009 (640 mm). The mean rainfall at the Mandurah station is 671 mm, with the 2010 total being one of the lowest rainfall totals recorded. As expected, rainfall intensity and hence totals were observed to be most significant during the winter months (May to September), with several months experiencing total rainfall exceeding 100 mm. In contrast some months, most notably December through February received rainfall totals less than 10 mm. Several large (>30 mm) individual rain events were identified during the

monitoring period, one in particular occurred in March 2010 toward the end of the summer dry season, where 60 mm was recorded in a 24 hr period. Of particular note is that no significant rainfall (>10 mm in 24 hrs) was recorded for three months prior to this event and no rainfall two weeks after. Evaporation data discussed in this study was taken from the same Mandurah BoM station (#9977) used to correlate our measure rainfall totals.

Ionic Chemistry

Ionic chemistry of potential source waters to Lake Clifton were investigated. Na⁺ and Cl⁻ dominate the ionic composition of both lake waters and the upper fresh water Aquifer groundwater. Cation dominance is in the order Na>Mg>Ca>K for the lake water and anion dominance is Cl>SO₄>HCO₃. Both cationic and anionic orders of the lake waters are maintained through the year, despite the previously outlined seasonal TDS shifts of 30 g.L⁻¹ between Autumn (May 70 g.L⁻¹) and Spring (September 40 g.L⁻¹). Both the unsaturated zone waters and the upper fresh water aquifer groundwater display cationic order of abundance as Na>Ca>Mg>K and an anionic order as Cl>HCO₃>SO₄. This is despite the unsaturated zone waters having much higher TDS (12 to 26 g.L⁻¹), than the upper fresh water aquifer. Rainfall ionic chemistry (Na>Mg>Ca>K and Cl>SO₄>HCO₃ - TDS <1 g.L⁻¹) and seawater ionic chemistry (Na>Mg>Ca>K and Cl>SO₄>HCO₃ - TDS 35 g.L⁻¹) measured in this study are similar in ionic composition to that stated by Hingston and Gailitis (1976) for the south-west coastal zone of Western Australia.

Isotope Hydrochemistry

Stable deuterium ($\delta^2\text{H}$) and oxygen ($\delta^{18}\text{O}$) isotope results display distinct variation between the upper fresh water aquifer, unsaturated zone waters, lake water and rainfall (Table 2). Superficial Aquifer $\delta^2\text{H}$ and $\delta^{18}\text{O}$ values range between -15 and -20 ‰ and -2.5 and -4.5 ‰ respectively. A single isotopic measurement for rainfall $\delta^2\text{H}$ (-13.2 ‰) and $\delta^{18}\text{O}$ (-4.3 ‰) was obtained and can be considered similar to that of the upper fresh aquifer. Isotope values for the unsaturated zone waters, $\delta^2\text{H}$ (-5.3 ‰) and $\delta^{18}\text{O}$ (-0.9 ‰), are more enriched than that seen for rainfall and the upper fresh water aquifer. The most enriched isotopic signature was evident for the Lake Clifton surface water, ranging between 6 to 24 ‰ for $\delta^2\text{H}$, and 0 and 5 ‰ for $\delta^{18}\text{O}$. Furthermore, seasonal variation was apparent in the isotopic composition of the lake water. June exhibited the least enriched values ($\delta^2\text{H}$ ~6 ‰, $\delta^{18}\text{O}$ ~0 ‰), while November displayed the most enriched $\delta^2\text{H}$ (20 ‰) and $\delta^{18}\text{O}$ (3 ‰) values.

DISCUSSION

Time series hydrological data presented in this study in conjunction with seasonal geochemical and isotopic analysis, provide insight into the hydrological functioning of the Lake Clifton System for the period 2008 to 2010. Previously seasonal shifts in hydrology were primarily interpreted from the 25 yr long term lake level and salinity monitoring program (Lane *et al* 2013), which consisted of twice-yearly September and

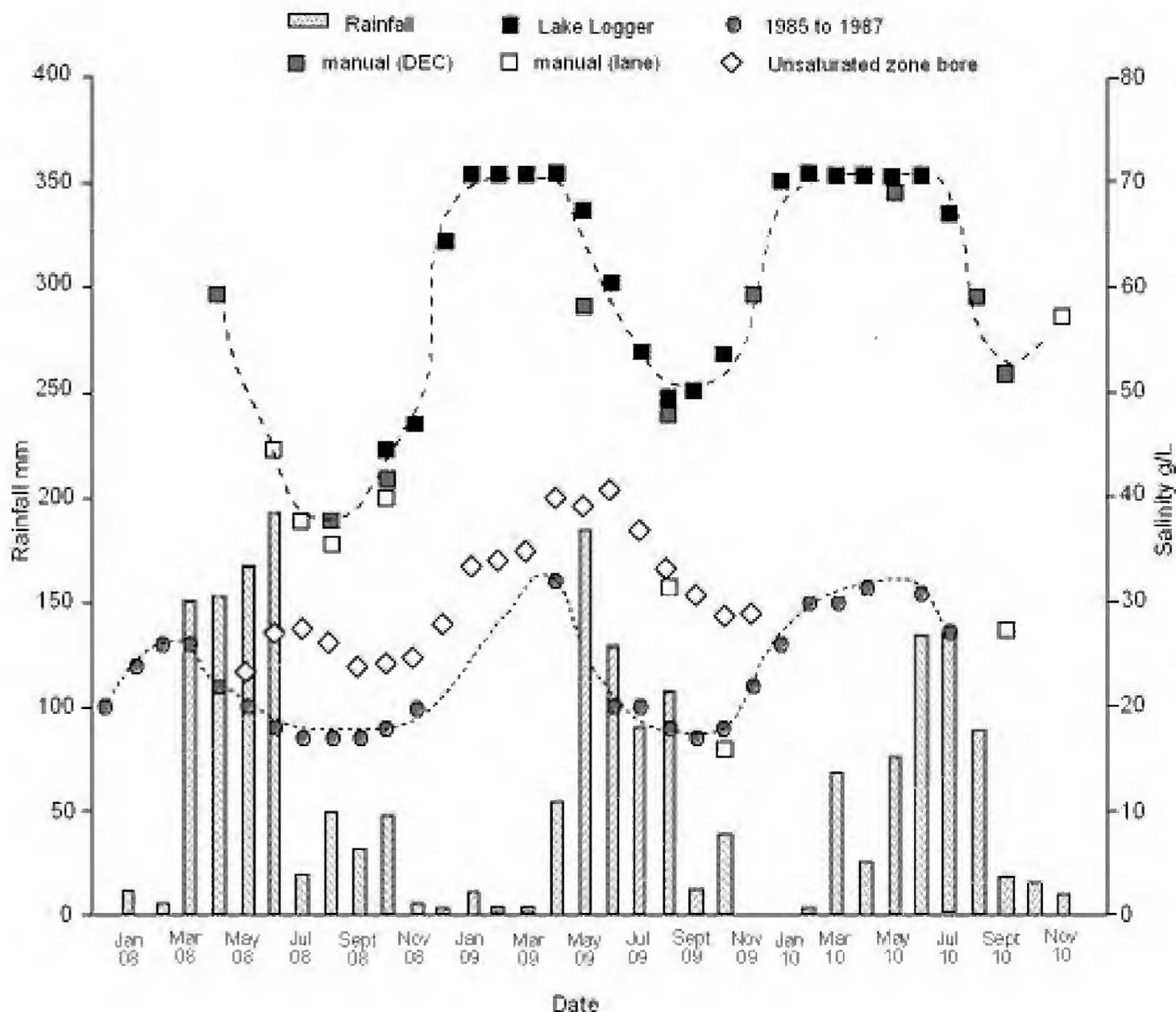


Figure 3. Manual and automated logger measured salinity concentrations (g.L^{-1}) for Lake Clifton and sub surface waters (meters of depth gauge local datum; +4.035 m AHD) bore for the November 2008 to November 2010 monitoring period. Simultaneous measurement data from Lane (*et al* 2013) also presented.

November measurements, taken when lake and salinity levels were anticipated to be at their respective peaks and troughs. This protocol followed the strategy employed by Moore (1987) who stated that maximum lake water levels occurred approximately four months after the anticipated July rainfall maximum. Our averaged monthly lake data confirm the Moore (1987) strategy with water level maximums and salinity minimums around September, two to three months after peak in rainfall totals. A strong relationship between the change in monthly average lake level and rainfall totals (Figure 4) is identified for the 2008 to 2010 monitoring period ($R^2 = 0.75$; $P < 0.001$). This relationship matches that developed using the 20-plus years of biannual data, used recently by Smith *et al* (2010) that show water levels in Lake Clifton are still highly dependent on rainfall.

Moore (1987) used the identification of this three to four-month delay between peaks in rainfall and lake

level as evidence of groundwater inflows into the lake to its importance to water levels in Lake Clifton. To quantify the contribution of groundwater infiltration for 1984, regional annual precipitation (762 mm), measured evaporation (1369 mm) and change in lake level were assessed. Moore (1987), assumed that 80 % of rainfall occurred between March and September and identified precipitation during this period to exceed evaporation by 112 mm. Lake Clifton water level however rose by 864 mm, meaning shallow groundwater inflow contributed significantly to lake level and hence composition in 1984. In order to assess the contributions of groundwater to lake level we repeated the calculations done by Moore (1987) using both our 2009 and 2010 seasonal data. Rainfall was seen to exceed evaporation by just 5 mm in 2009 and was below evaporation by 125 mm in 2010 during the winter rain periods. For both these years' lake levels fluctuated by 680 mm and 530 mm respectively,

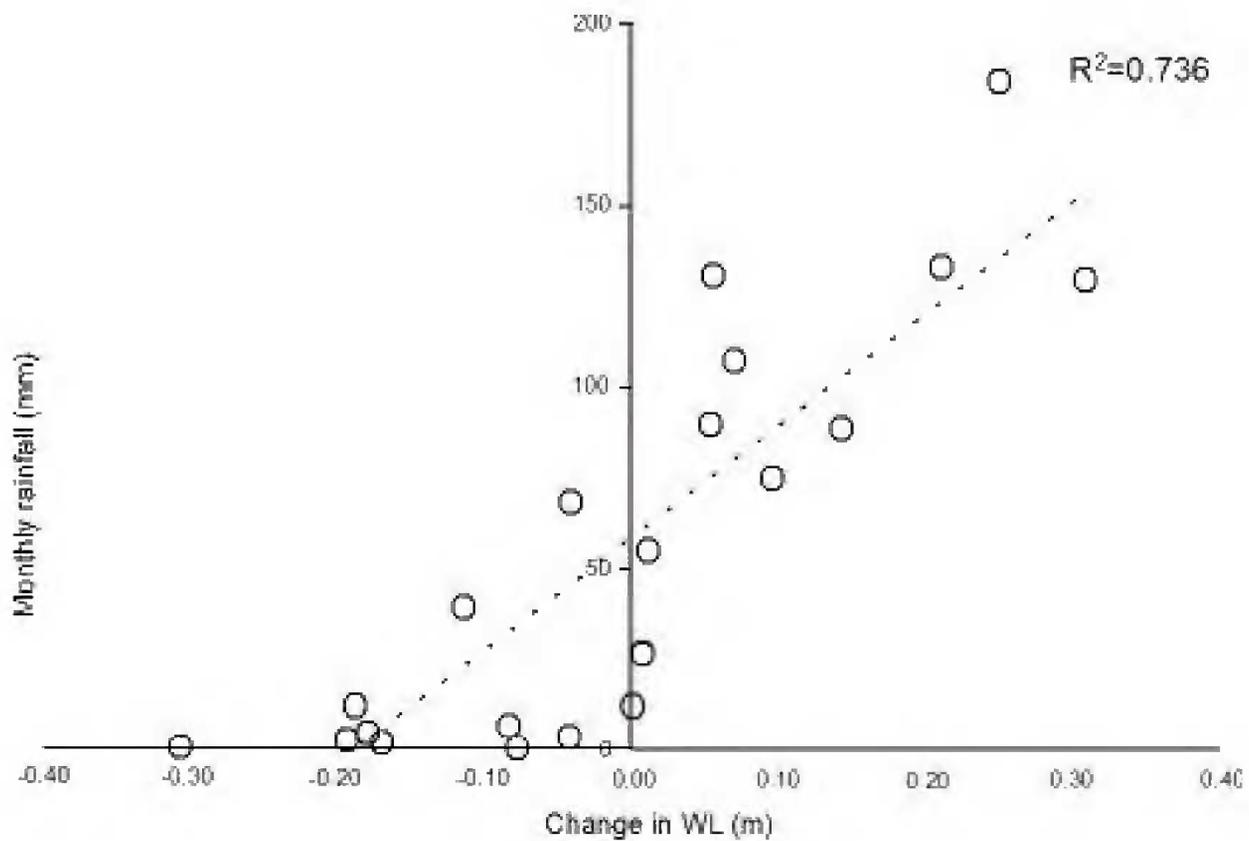


Figure 4. Lake water level and lake edge sub-surface waters response to 60mm rainfall event over one week in March 2010. Note during the same period lake salinity remained at 70 g.L^{-1} the maximum measurement capacity of the Hydrosonde logger.

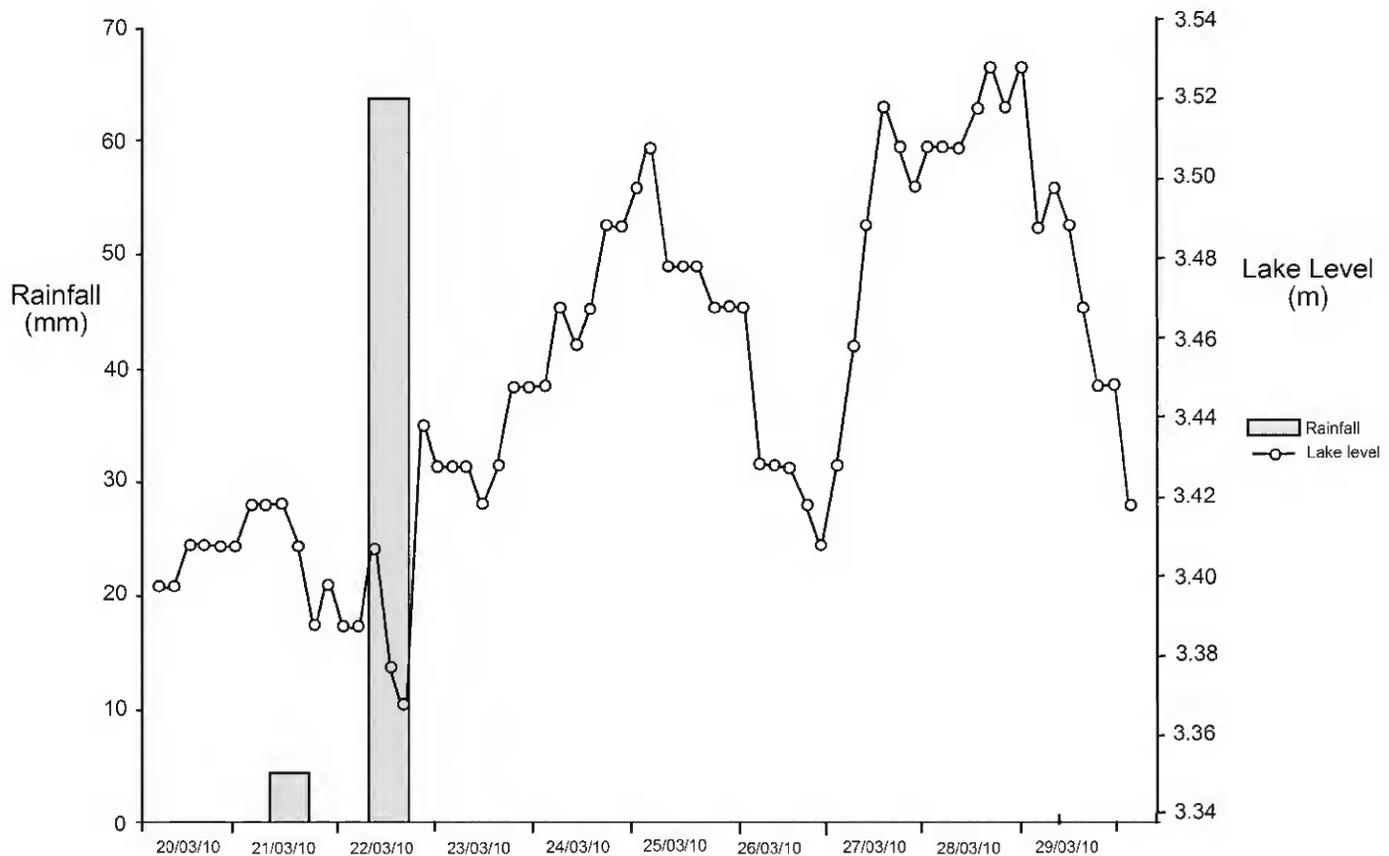


Figure 5. Relationship between monthly change in Lake Clifton water level and accumulated monthly rainfall for the 2008 to 2010 period.

hence according to these parameters groundwater inflow contributed 752 mm in 1984, 675 mm in 2009 and 655 mm in 2010. These data indicate a possible decadal scale reduction in groundwater input to the lake, and that its water balance is highly dependent on winter rainfall totals and winter evaporation deficit.

Further to the Moore (1987) findings, Knott *et al* (2003) also argued for the importance of contributions by groundwater to the Lake Clifton water balance. Looking at the long term (1980 – 2000) salinity, lake level and rainfall data, they identified no relationship between annual spring-time salinity levels, thus implicating groundwater inflow as a key driver of lake salinity. Close inspection of our daily measured lake levels identifies immediate responses to rainfall, which further supports both rainfall and groundwater recharge as important input components to Lake Clifton. In March 2010, at the end of the summer dry season the lake area experienced a significant rainfall event (60 mm in 24 hours). In the following 48 hrs after the rain event lake level rose by 150 mm. A second 100 mm increase in lake level was identified four days after the rainfall event

(Figure 5). A brief increase in water in the unsaturated zone proximal to the lakes edge of 100 mm immediately after the rain event was also identified. In comparison there was no notable change in water levels in the upper fresh water aquifer. Hence this two-phase increase in lake levels resulting from this isolated rainfall event is interpreted as comprising an initial phase of direct rainfall recharge, followed by a second phase of infiltration through the unsaturated zone combined with and possible surface runoff. Surface water recharge into Lake Clifton has been noted before by Davies and Lane (1996), but only after rainfall events of in excess of 10 mm in a 48 hr period, and even then it is thought to only contribute minimally to the overall water balance of Lake Clifton. However, reduction in the area of native vegetation buffer zones around the lake over the last two decades, may have allowed for a potential increase in surface water runoff into Lake Clifton. Interestingly lake salinity during the storm period where the sharp increase in water level was observed, remained at 70 g.L⁻¹ the maximum reading for the multi-sonde logger. Hence whether this rain event affected salinity in the lake cannot be assessed.

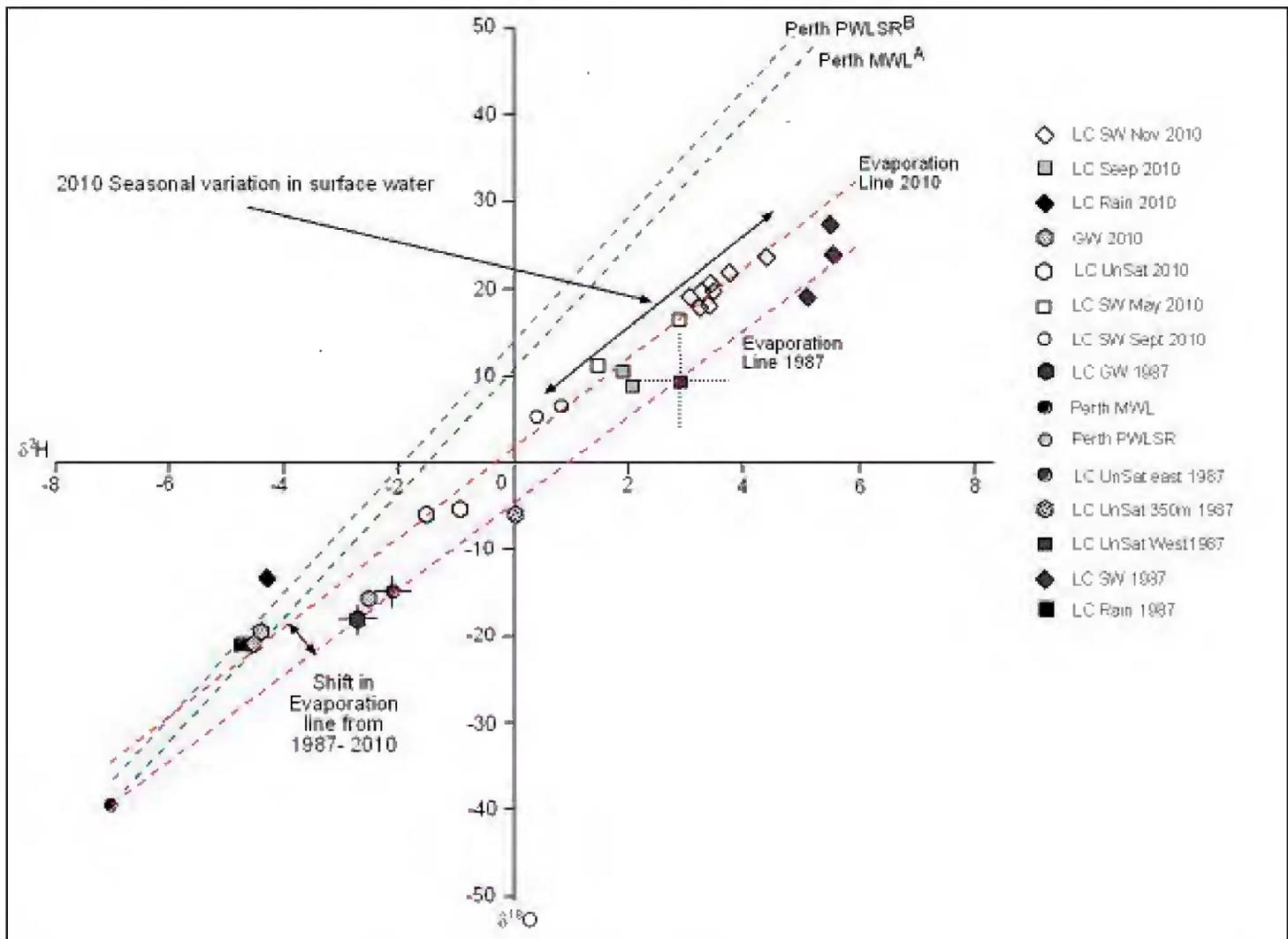


Figure 6. $\delta^2\text{H}$ and $\delta^{18}\text{O}$ data for Lake Clifton surface water, groundwater (Superficial Aquifer), sub-surface waters (1 m below ground level) and rainfall. Surface water isotopic data represents June, September and November 2010. Also included are $\delta^2\text{H}$ and $\delta^{18}\text{O}$ data for sub-surface waters from Moore (*et al* 1987) and for seep waters (sub-surface water expression) for November 2010. Evident is a shift in the intersection between the evaporation lines for 1987 and 2010 the local meteoric water lines (LMWL) for Perth (Turner and Townley 2006, Hughes and Crawford 2012).

Variation in Lake Clifton's TDS is seasonal and similar to those identified for lake levels. Lowest yearly recordings of between 35 and 50 g.L⁻¹, are evident in September each year, corresponding to peaks in water level. Highest salinity (>70 g.L⁻¹ TDS) concentration was identified in the summer months, when lake levels are at their lowest. However, the exact timing and value of the peak could not be confirmed as many salinity readings exceeded the detection limitations of the multi-sonde instrumentation. A manual measurement of 74 g.L⁻¹ for May 2010 was the highest salinity reading recorded during the two-year monitoring period. Between 2008 and 2010, Lane *et al* (2013) also measured lake water TDS at the inner and outer sedge areas, where ground water seepage is thought to enter the lake. Of further interest is that the number of months in 2010 where salinity (EC) exceeded 70 g.L⁻¹ was 6 compared to 4 months in 2009, a year that experienced over 100 mm extra rainfall, further implicating rainfall as an important factor in lake water salinity. It would also appear that the salinity minimum observed each spring (Figure 3) increased slightly from 2008 to 2010 following the long-term trend of increasing lake salinity, however seasonal effects would need to be considered to evaluate this potential trend over time in more detail. Our monthly data supported by that from Lane *et al* (2013) confirms the Smith *et al* (2010) hypothesis that annual minimum lake salinity (EC) is 40 to 50 g.L⁻¹ and occurs between August through October, implying that Lake Clifton can no longer be considered hyposaline at any stage of the year, like it had been categorised in previously (Moore, 1987, 2003).

In most hydrological systems, evaporation from open water bodies is the principle isotopic fractionation mechanism and the driving of evaporative isotopic enrichment. Variation in $\delta^{18}\text{O}$ and $\delta^2\text{H}$ in lake waters is strongly influenced by its temperature, salinity and relative humidity (e.g. Kendall and Caldwell, 1998). Lake Clifton's surface water stable isotopic data ($\delta^{18}\text{O}$ and $\delta^2\text{H}$) exhibit characteristics expected for a coastal lake system in the south-west of Western Australia, whose water composition is dominated by oceanic characteristics that are subjected to strong evaporation processes (e.g. Sharma and Hughes, 1985, Marimuthu *et al* 2005, Turner and Townley, 2006).

Isotopic data, $\delta^2\text{H}$ -18.25 ‰ (stdev 2.37; n = 4) and $\delta^{18}\text{O}$ -3.82 ‰ (stdev 0.93; n = 4) for the upper fresh aquifer is similar to regional rainfall ($\delta^2\text{H}$ -17.4 ‰; $\delta^{18}\text{O}$ -3.85 ‰) and falls on the well-established Local Meteoric Water Line (LMWL) for Perth, Western Australia $\delta^2\text{H} = 7.15*\delta^{18}\text{O} + 10.6$ (e.g. Turner and Townley, 2006, Liu *et al* 2010, Hughes and Crawford, 2012). The evaporation line, the linear equation that represents the evolution of evaporated water (e.g. Allison *et al* 1979), is $\delta^2\text{H} = 5.18*\delta^{18}\text{O} + 1.61$ has a lower slope than the LMWL as evaporation causes deviations from the LMWL (Gibson *et al* 1993). Lake Clifton surface waters are significantly more enriched than the waters of the unsaturated zone, upper fresh groundwater and rainfall, indicating a strong evaporative influence. surface seep waters identified on the eastern edge of Lake Clifton during the winter rain season display more enriched $\delta^{18}\text{O}$ and $\delta^2\text{H}$ than the upper fresh aquifer groundwater due to its longer period of exposure at the surface and evaporative isotopic enrichment.

$\delta^2\text{H}$ and $\delta^{18}\text{O}$ isotopic data for Lake Clifton for the three months of June, September and November in conjunction with monthly salinity data confirm the impact of seasonal evaporative on lake chemistry. September (n=2) displays the least enriched $\delta^2\text{H}$ and $\delta^{18}\text{O}$ values with June (n=2) more enriched and November (n=8) the most enriched. September is also the month where minimum salinity is observed suggesting that this is the month where the lake waters composition is most likely influenced by combined contributions from rainfall and groundwater inflows.

Besides seasonal evaporation processes, $\delta^2\text{H}$ and $\delta^{18}\text{O}$ data has been used previously (Moore, 1987, 1993 and Moore and Turner, 1988) to identify the presence of groundwater infiltration into eastern Lake Clifton. In that study sub-surface waters sampled across the first 350 m of the eastern side of the lake derived an isotopic signature ($\delta^2\text{H} \sim -14.9$ ‰ and $\delta^{18}\text{O} \sim -2.11$ ‰) similar to regional groundwater, but much less enriched than the lake water itself ($\delta^2\text{H} \sim 5$ ‰ and $\delta^{18}\text{O} \sim 25$ ‰). $\delta^2\text{H}$ and $\delta^{18}\text{O}$ values for unsaturated zone waters more than 350 m west from the lake's eastern edge were much more enriched with signatures more akin to lake waters. While similar groundwater $\delta^2\text{H}$ and $\delta^{18}\text{O}$ values are evident for both 1987 and 2010 data, unsaturated zone waters analysed in 1987 are clearly less enriched than those in 2010. Comparisons of evaporation lines for 1987 ($\delta^2\text{H} = 4.98*\delta^{18}\text{O} - 4.55$) for the Moore (1988,1993) data set and for 2010 sees the 1987 evaporation line having greater separation from the LMWL than the 2010 evaporation line. Furthermore, the $\delta^2\text{H}$ and $\delta^{18}\text{O}$ intersection point of the two evaporation lines with the LMWL are different (1987 ~ -7 ‰ and -40 ‰ and 2010 ~ -4 ‰ and -18 ‰, for $\delta^2\text{H}$ and $\delta^{18}\text{O}$ respectively). The intersection of the evaporation line with the LMWL is a representation of the average composition of source water entering a lake system (e.g. Gibson *et al* 1993, Walker and Krabbenhoft, 1998, Cartwright *et al* 2004, 2013). Thus we interpret the shift in the evaporation line signature between 1987 and 2010 as evidence of a shift in the water balance of Lake Clifton System due to a changing source of water. This hypothesis requires further validation considering more recent data and also greater number of groundwater samples. This change could manifest from a reduction in total rainfall and groundwater inflow or a change in the composition source of groundwater. A preliminary linear mixing model of surface waters using $\delta^{18}\text{O}$ and Cl⁻ data following that applied by Price *et al* (2012) implies a dominant source of groundwater for 2010 to the lake at an approximate $\delta^{18}\text{O}$ value of -4 ‰, which is similar to that identified for the upper fresh aquifer on the eastern side of the lake.

Rosen *et al* (1996) reported 1995 ionic abundance order for lake waters as Na>Mg>Ca>K and Cl>SO₄>HCO₃, in proportions similar to seawater. These findings were in accordance with numerous other hydro-chemical studies of the lake (Williams and Buckney, 1976, Moore, 1987, Burke and Knott, 1989). Moore (1987) found that the regional groundwater flowing into Lake Clifton had ionic abundances of Na>Ca>Mg>K and Cl>HCO₃>SO₄, that had been consistent over time. Comparisons of our 2010 data to these previous studies identify similar order of abundances for both surface and ground waters. However, significant increases in concentration of all

major cations (Ca, K, Na, Mg) and Cl⁻ (Figures 7a,b,c) are evident for lake waters since the 1970s. Increases in cations and Cl⁻ in the upper fresh groundwater, albeit of a lesser magnitude than that evident in lake water (Figures 8a,b,c) are also apparent since the 1980s. Comparisons of molar ratios of water bodies shed more light on this increase by suggesting a possible changing hydro-chemistry of groundwater. Falling Ca/Cl and Mg/Cl ratios in lake waters and the upper fresh aquifer ground waters of the system between 1984 and 2010 (Figures 7d, 8d) combined with the increasing ionic concentrations suggest a general shift to the ionic chemistry of seawater.

It is well established from previous studies (e.g. Knott *et al* 2003, Smith *et al* 2010) that Lake Clifton has been experiencing increasing salinity over the last few decades, the causes of which have been tackled by several investigations. Barr (2003) used the established

data sets derived and water balance for the lake and examined three possible mechanisms for the increasing lake salinity. These were 1) observed reductions in rainfall and reduced freshwater inflow; 2) the dewatering of the Dawesville Channel to the north of Lake Clifton, causing a rise in the level of the underlying saline groundwater; and 3) bore water extraction within the catchment area reducing freshwater input to the lake. Results from modelling these scenarios indicated that the lake system was extremely sensitive to both rainfall and evaporation rates. Thus Barr (2003) concluded that the reduction in water levels and increasing salinity were most likely a result of changing climatic conditions.

Further to the work done by Barr (2003), Knott *et al* (2003) compared lake salt mass and rainfall to determine whether rainfall was a key driving factor in determining lake salinity. Knott *et al* (2003) investigated data from

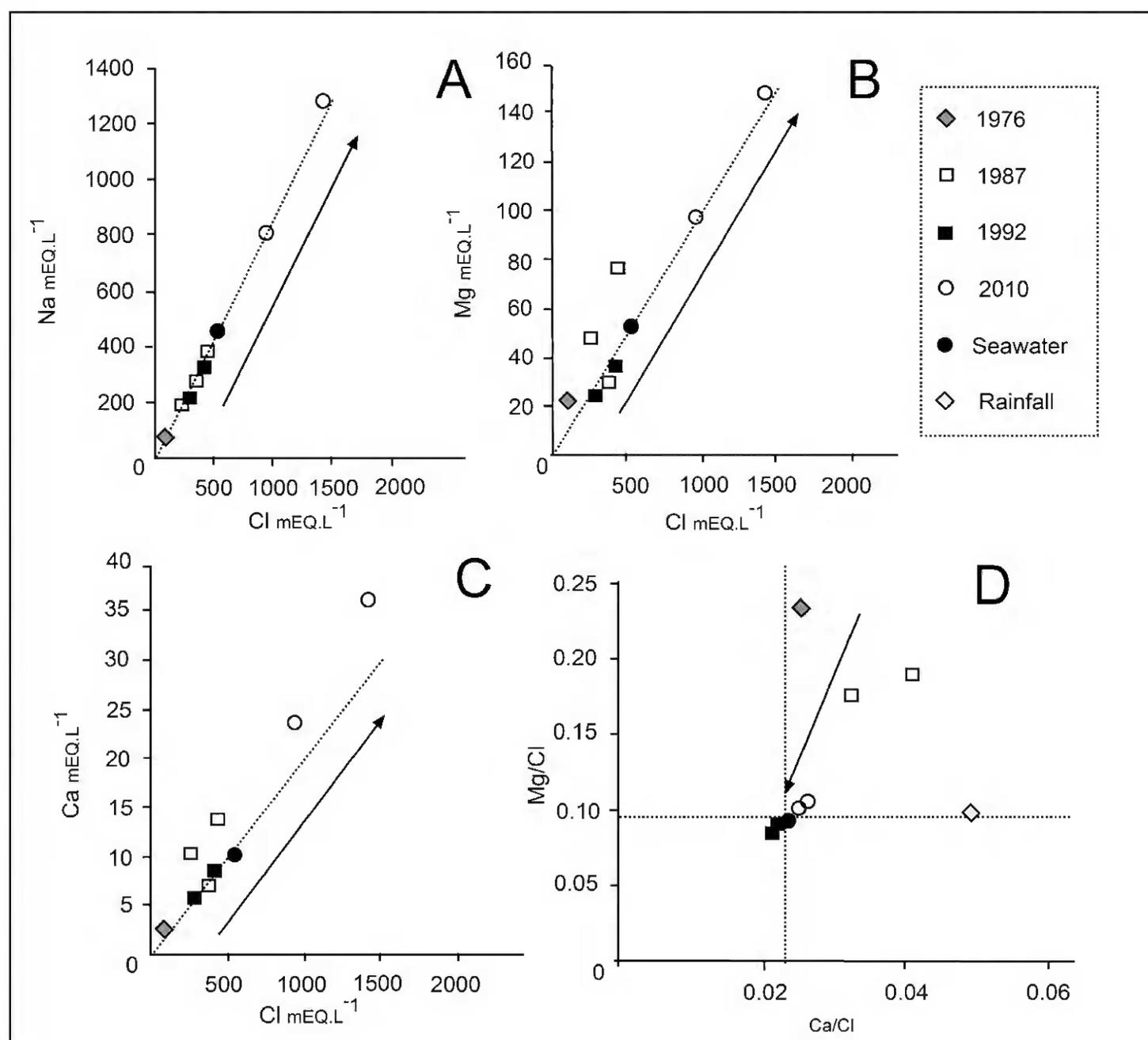


Figure 7. Surface water Na (a), Mg (b) and Ca (c) ionic concentrations versus Cl ionic concentrations (mEq.L⁻¹). Our 2010 data is compared to similar data from 1976 (Williams and Buckley 1976), 1987 (Moore 1987), and 1992 (Rosen *et al* 1996). Mg/Cl versus Ca/Cl ratios (d) for the same data sets are also presented and compared to ratios for rainfall and seawater (Hingston and Gailitis 1976).

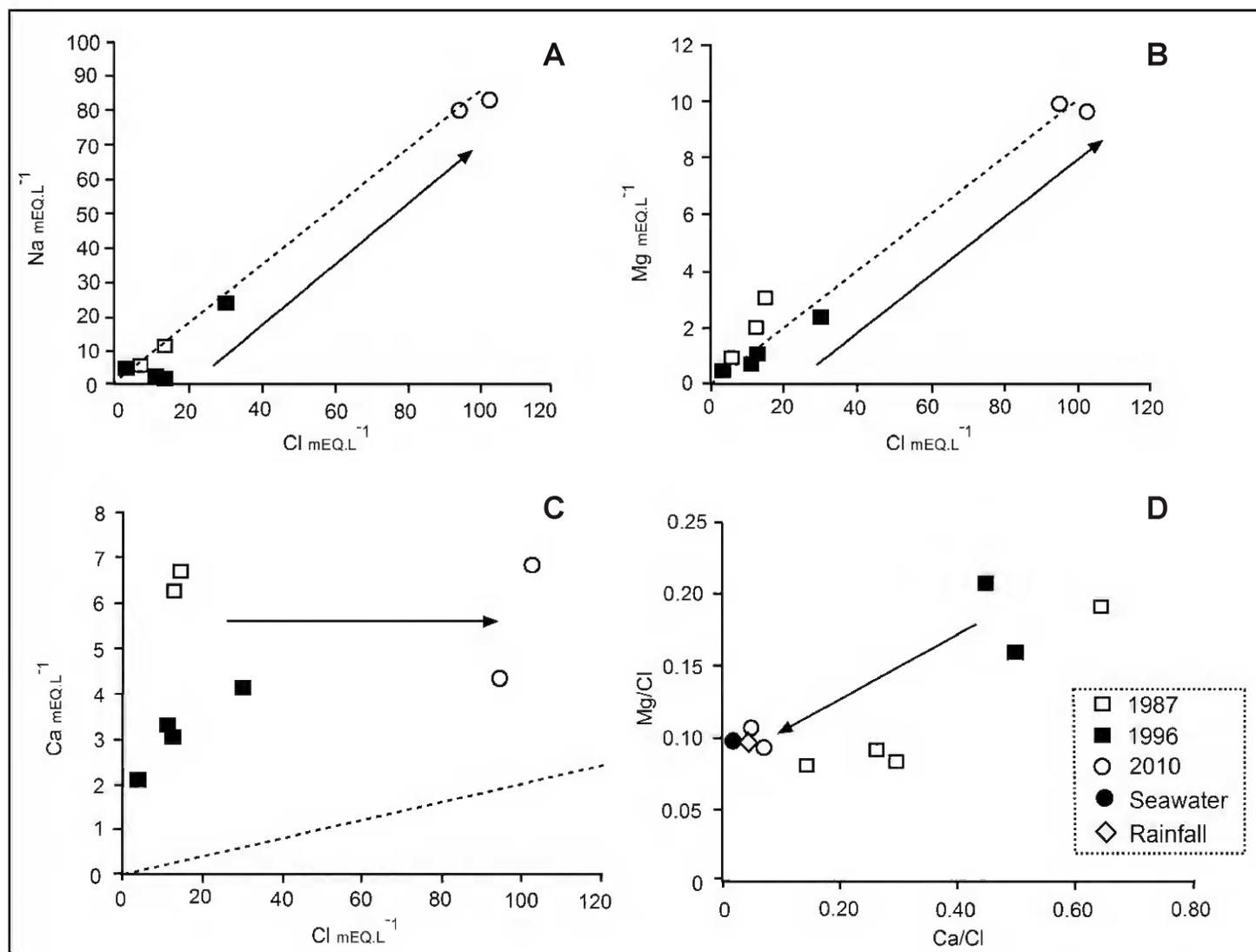


Figure 8. Groundwater (upper fresh water aquifer) Na (a), Mg (b) and Ca (c) ionic concentrations versus Cl ionic concentrations (mEq.L⁻¹). Our 2010 data is compared to similar data for 1987 (Moore 1987) and 1996 (Western Australia Department of Water database 1996). Mg/Cl versus Ca/Cl ratios (d) for the same data sets are also presented and compared to ratios for rainfall and seawater (Hingston and Gailitis 1976).

years where increased rainfall, and subsequent rises in lake levels coincided with a reduction in salinity levels, finding a lack of correlation, with salinity increasing. The rising salinity was attributed to an increase in saline water inflowing to the lake system in comparison to fresh ground water, diluting any effects of variable rainfall. Our data presented here supports the findings by Barr (2003) and Knott *et al* (2003) that changing composition of the upper fresh aquifer groundwater is a key driver in the changing chemical composition of Lake Clifton.

The salinity, $\delta^2\text{H}$, $\delta^{18}\text{O}$, and ionic data presented here supports the previous studies suggesting that salinity continues to rise in Lake Clifton, reaching levels not previously seen in the last several decades. Our data suggest that groundwater and rainfall associated surface water both continue to contribute to the lake's hydrological composition, however a shift in the chemical composition of the upper fresh aquifer seems likely. It is possible that saline water from the lake (or its underlying salt water interface) could be increasing regional groundwater salinity, however current data sets are insufficient enough to quantify this increase.

Beggs (2014) used a combination of the data presented herein and the long-term data from Lane *et al* (2013) to reconstruct current and predict future water balances of Lake Clifton, identifying insight into the lakes shifting hydrology. The model calculated that lake levels are declining by an average of 0.12 m per year and end-of winter salinity is increasing by 1.2 g/L per year. Total salt mass has increased by 2.5 times since 1985 and total groundwater inflows are estimated to have increased by approximately 40,000 m³ annually. This combined increase could not be created solely by effects associated with increased abstraction of fresher groundwater and that seawater intrusion from the west is likely to have increased in the last few years, even though this was discounted by Barr (2003).

CONCLUSION

This investigation provides an enhanced understanding of the hydrological functioning of Lake Clifton, on which the existence of the Thrombolite reef located on the eastern edge of the lake relies. Hydro-physical, geochemical and isotopic data for the hydrological

system indicate that groundwater and precipitation both contribute to the lakes water balance. Comparisons of our recent data with data sets over the last 20 to 30 years, however suggest that the hydrological balance of the lake, in particular its geochemistry and that of the groundwater infiltrating into its eastern edge has been undergoing alterations during this time frame. It is most likely that a drying climate, increasing temperatures and reduced rainfall, as hypothesized by Barr (2003) are causing a reduction in the amount of freshwater that enters Lake Clifton directly as sub-surface recharge. In turn infiltration of saline groundwater from the Hayward chain of hypersaline lakes to Lake Clifton is creating a redistribution of salt mass from the groundwater system to Lake Clifton (Noble, 2010). This salt was originally concentrated by evaporation in other lakes within the Yalgorup Lakes system and the redistribution of the greater lake system salt balance is ultimately threatening the ecology of this highly significant biodiversity asset and the potability of the upper freshwater local groundwater.

ACKNOWLEDGEMENTS

This work was funded by the Species and Communities Branch of the Department of Parks and Wildlife, Western Australia. We would like to thank the Mandurah Office of the Department of Parks and Wildlife, Western Australia with their help in field work logistics. We acknowledge Department of Water, Western Australia, for providing access to their bores and groundwater database. Thanks for Erick Bestland and Lindsay Bourke for their contributions during the editorial process.

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